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HYSTERESIS EFFECTS ON SEXTUPOLE MOMENTS OF TEVATRON DIPOLES AT INJECTION CURRENT

Bruce C. Brown

Injection into the Tevatron will take place at an energy of about 150 GeV or a current of 660A. At that current it will be necessary to compensate as fully as possible for the higher harmonics of the Tevatron magnets. In particular, the sextupole moment of the superconducting dipole magnets is capable of substantial differences due to hysteresis which could adversely affect the beam at injection. A preliminary study of the effects of various ramp parameters has been carried out on the body field (downstream center probe location) of one dipole and at all three probe locations in another dipole using the MTF Harmonic analysis system and the program DCH. This paper will present results from this study in order to provide for injection power supply parameters and to allow planning of the doubler injection scheme in more detail.

Figures 1 and 2 show model ramps (with only straight line segments) which idealize some ramp parameters which are significant for injection fields. If we call level A the reset level, level B the injection current, level C the flattop current and level B' the overshoot level then we want to study the harmonic content of the field with special attention to the sextupole component for B of 660 A or 150 GeV and various levels of A, B', and C.

The standard MTF system and DCH program were used to acquire this data and this imposed several limitations (hopefully not important) to the data. Ramping was always done at 100 A/sec as the Transrex controls at MTF have been found to overshoot on the down ramp under some conditions when faster ramp rates are allowed. The desired ramp shape was simulated by successively requesting the desired currents. This ignors any hysteresis changes which may be caused by either ramp rate or the duration of any portion of the ramp. It basically assumes that the results will depend only on the order in which previous values of current are achieved. Using both the current shunt amplified and displayed on an oscilloscope and a DVM viewing the shunt directly and read visually, the overshoot properties of the ramp were examined. The current goes from the value achieved before the ramp to the final value with no observable over - or undershoot with a sensitivity of certainly less than an Ampere and probably less than one half of that. The quality of the data obtained in the overshoot test supports this observation. Data on all harmonics was taken and preserved for each run but only the sextupole data will be presented here.

Figures 3 and 4 present data on the hysteresis of the magnets (central field portion only) around one of the loops of typical interest. In Figure 3 the data is presented in Standard Tevatron Units which are normalized to the central dipole field. Figure 4 presents somewhat different insights by plotting the data proportional to the actual sextupole field strength by multiplying the harmonic component b_2 by the current in kA. The data began with a ramp which started at zero current and proceeded to 4000A, then stepped down to 400A, then was cycled back up to 4000A, observing that the curve follows very closely the previous one within a few hundred Amps above the minimum current point. Table 1 provides the raw data to allow one to make the comparison.

For each probe location, four sets of data were taken to answer the following questions:

a) What repeatibility do we achieve on separate ramps.
b) What change in sextupole component at 660A do we observe as the peak current C is changed.
c) What repeatibility is required in achieving the reset current A as the choice of values for A is varied.
d) How much overshoot is allowed in seeking an injection level B.

HARMONIC REPEATIBILITY

Using 5 successive ramps, harmonics were measured and analysed under conditions which were believed to represent re-measurement of the same conditions. Results gave mean and standard deviation as follows:

TB1Ø24	Center Probe Position	Mean	7.91	σ = .109
TBØ349	Upstream Probe Position	Mean	-4.647	σ = .077
TBØ349	Center Probe Position	Mean	15.90	σ = .071
TBØ349	Downstream Probe Position	Mean	-4.599	σ = .047

We can assume that the following measurements have errors in the measurement technique of this magnitude. Repeated measurements on the same ramp were not carried out but would be expected to yield about the same range of values.

EFFECT OF MAXIMUM CURRENT OF RAMP

The maximum current in a hysteresis loop sets the levels of persistent current. No attempt was made to study properly the effect of beginning these tests while the coil had a history built in. Standard MTF Hysteresis ramps 0A-4000A-0A at 200/Asec were carried out, then data on various alternative ramps recorded. For TC1Ø24 the effect of previous cycles was sought by ramping to the desired maximum current down to reset at 400A, and then to 660A, repeating this 3 times, then taking data at 660A on the 4th and 5th cycles. The data is plotted in Figure 5. No pattern of differences between 4th and 5th cycle data was apparent so data was taken again with only one pre-ramp around the desired loop. It is plotted separately on Figure 5. A linear fit gives a slope to Δb_2 of .2 unit 1kA. Similar data were taken for flattop values 700A to 4000A for all three probe locations on TB0349. No pre-ramps were used to obtain this data. Successive currents were taken in order. Data for end probe locations follow the trend of the center probe location data. Data averaged over the magnet is plotted in Figure 6. The linear slope for 2000-4000A is .24 units /kA.

EFFECT OF RESET LEVEL OF RAMP

The reset level effect was studied for 4000A peak currents. Data taken on TB1Ø24 is shown in Figure 7. Data for the 3 probe locations on TBØ349 are shown in Figures 8, 9 and 10 while Figure 11 gives the TBØ349 data averaged over the magnet. Here we see that the hysteresis effects are approximately the same magnitude in center and ends. In particular, the center cancels the magnitude of the end sextupole field, however, the hysteresis in the body is not cancelled in the ends. The data for different reset levels are taken on successive ramps.

To parameterize this data, we plot it by subtracting the value at 0A reset level and plotting.

$$\Delta b_2(I_A)=b_2(I_A)-b_2(I_A=0)$$

on semilog paper. For each portion of TBØ349, the results were plotted on Figure 12. We see that they agree adequately. When averaged over the magnet length we find the result plotted in Figure 13. Keep in mind that Δb is poorly determined as limited by the σ=.07 units shown previously. When Δb is fitted the resulting parameterization is shown on Figure 13.

$$b_2(I_A) = b_2(I_A=0) + 1.159 \times 10^{-2} e^{8.07 I_A(kA)}$$

where b_2 is measured at 660A.

$$\frac{db_2}{dI_A} = 9.353 \times 10^{-2} e^{8.07 I_A(kA)}$$

At 400A, 500A, 550A we have slopes of 2.36×10^{-3}, 5.29×10^{-3} and 7.92×10^{-3} units/Amp.

RAMP OVERSHOOT EFFECT

Using a flattop current of C=4000A, a reset value of A=400A and seeking an injection current B = 660A we studied the effects of allowing an overshoot to B' before going to B. Again, since we did no new programming, the value B' was sustained until 660A could be requested - a few seconds at least. Data from first running on TB1Ø24 is shown on Figure 14. Data on a more relavant scale are shown in Figure 15 for TB1Ø24 (center probe location) and Figure 16 for TBØ349 (averaged over the magnet). We see that for small overshoot currents, a linear increase in sextupole moment is observed. Such a linear fit is shown for TBØ349 in Figure 16 giving a slope of .21 units/Amp. while in Figure 15 the slope from a linear fit is .24 unit/Amp.

CONCLUSIONS

Injection to the Tevatron at a current of 660A will require control of the ramp at reset currents to avoid a sextupole change of .024 units for a 10 amp error in reaching 400A reset level and control of overshoot on approaching 660A to avoid .021 units of sextupole for 100mA of overshoot. A retuning corresponding to .2 units/1KA change in flattop level must be planned for in designing programs for injection control. Further studies are planned to provide data on more magnets and more ramp conditions.

I would like to thank the MTF operations staff for assistance in these studies.

Note Added: We have recently observed an apparent time constant in the magnets which may have some effect on this data but the internal consistancy of this data and the nature of our new observations suggest that this data may be correct if incomplete.

Table 1. TBØ349 Sextupole Hysteresis Data in Bodyfield

Current Amps	b_2 $\times 10^{-4}$	$b_2 \times I(kA)$ $\times 10^{-4}$
0	--	--
200	-9.003	-1.80
660	15.55	10.263
2000	20.03	40.06
4000	19.48	77.92
2000	21.34	42.68
660	24.62	16.25
400	29.06	11.62
450	15.26	6.87
660	15.53	10.25
1000	18.19	18.19
2000	20.01	40.02
4000	19.45	77.8
2000	21.33	42.66
660	24.61	16.24
400	29.27	11.71
200	43.84	8.77

FERMILAB ENGINEERING NOTE	SECTION -6-	PROJECT	SERIAL-CATEGORY	PAGE

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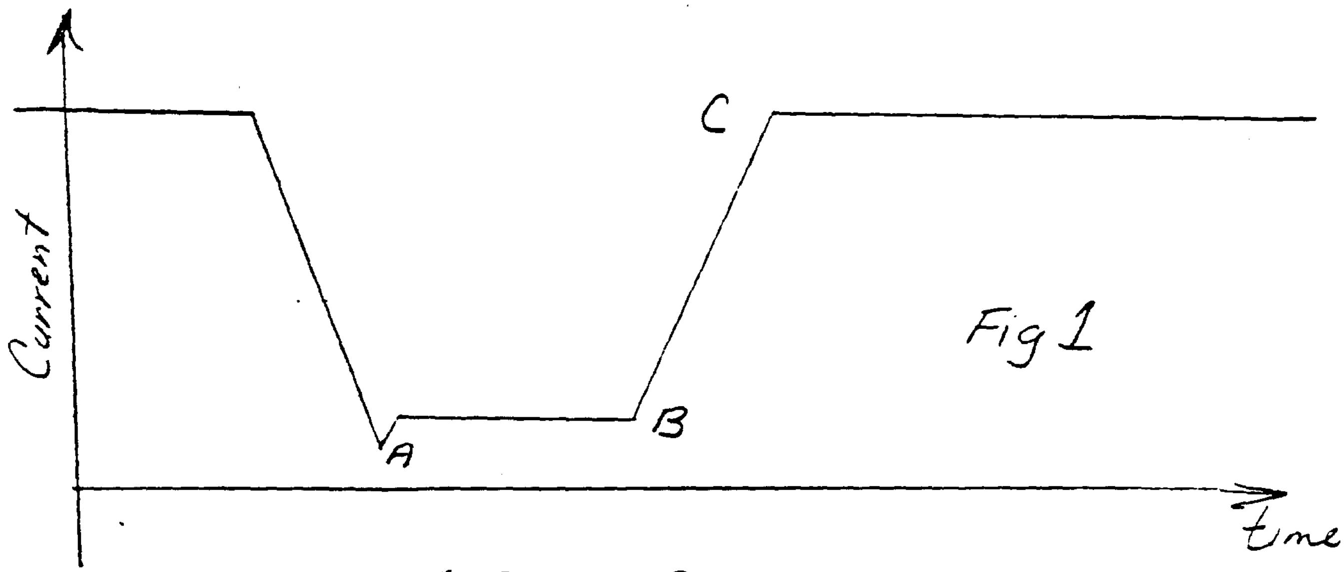
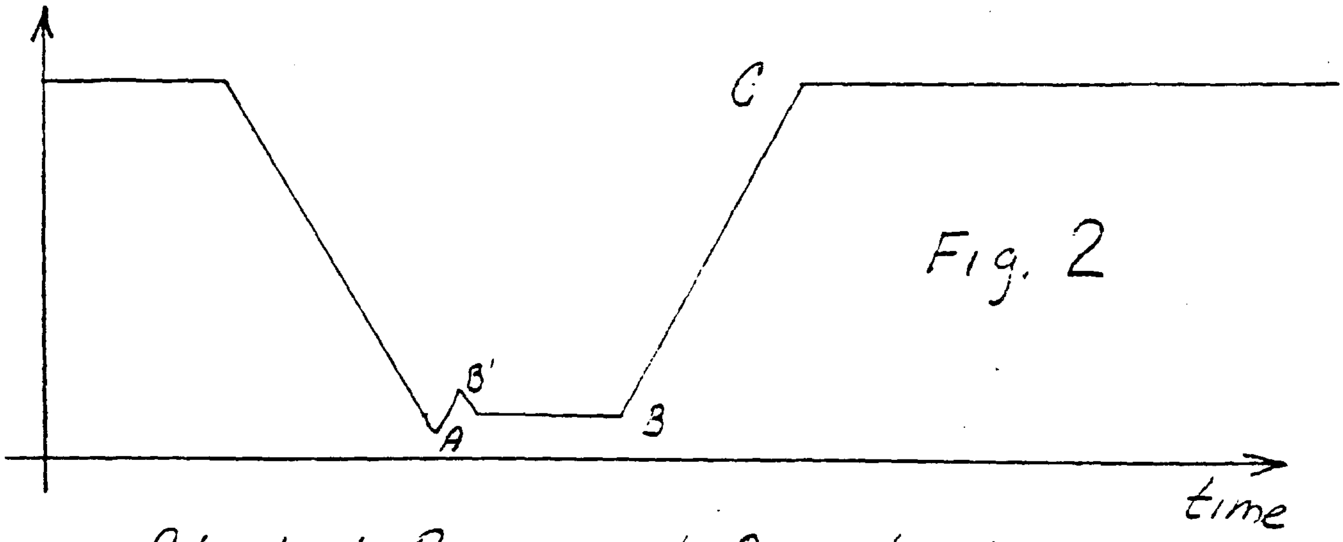


"Standard" Ramp Shape Assumed for Tevatron Ramping

Define C = Flattop Current
B = Injection Current
A = Reset Current



Standard Ramp with Overshoot

Define B' = Injection Overshoot Current

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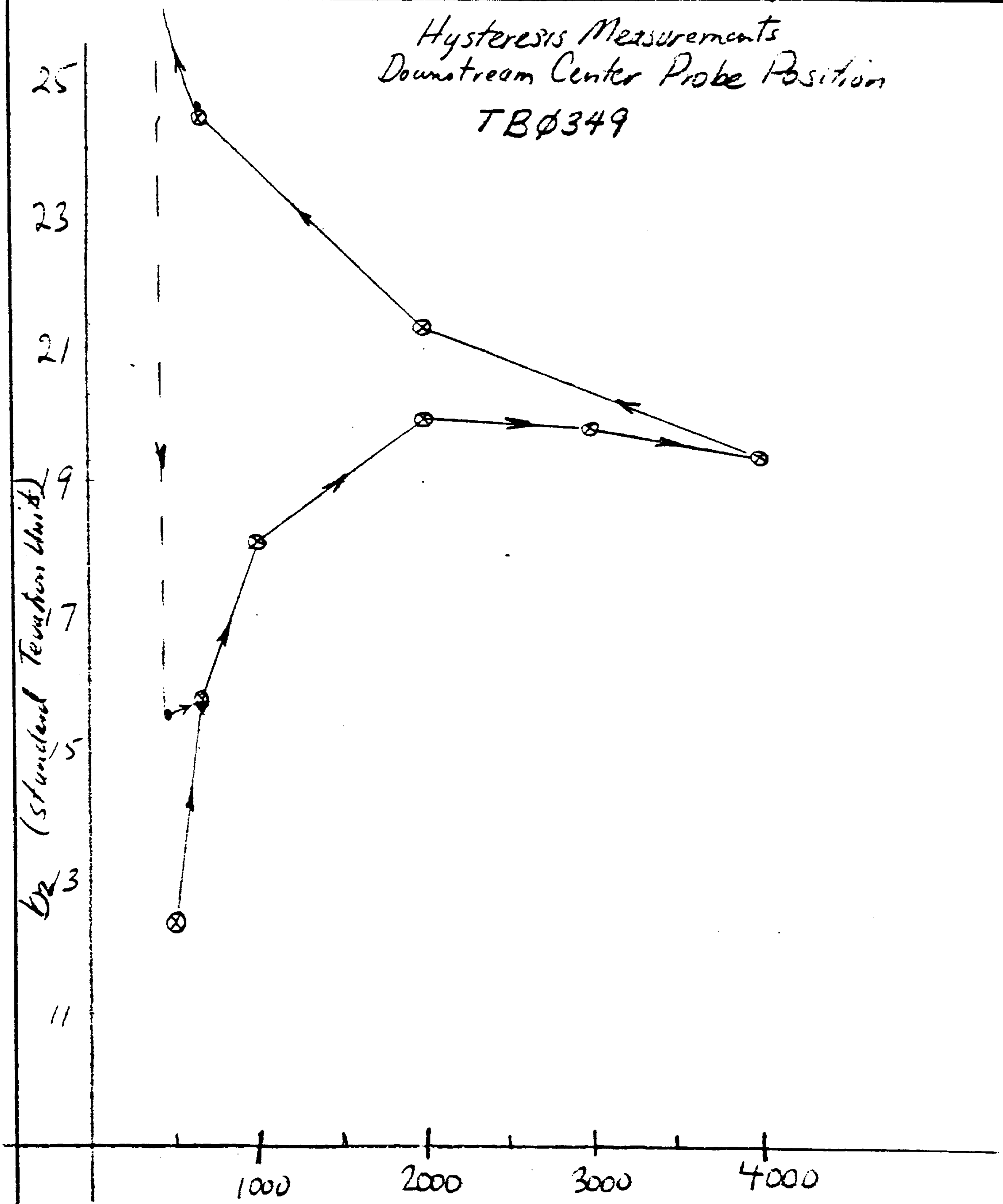

FIG. 3

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SECTION -8-

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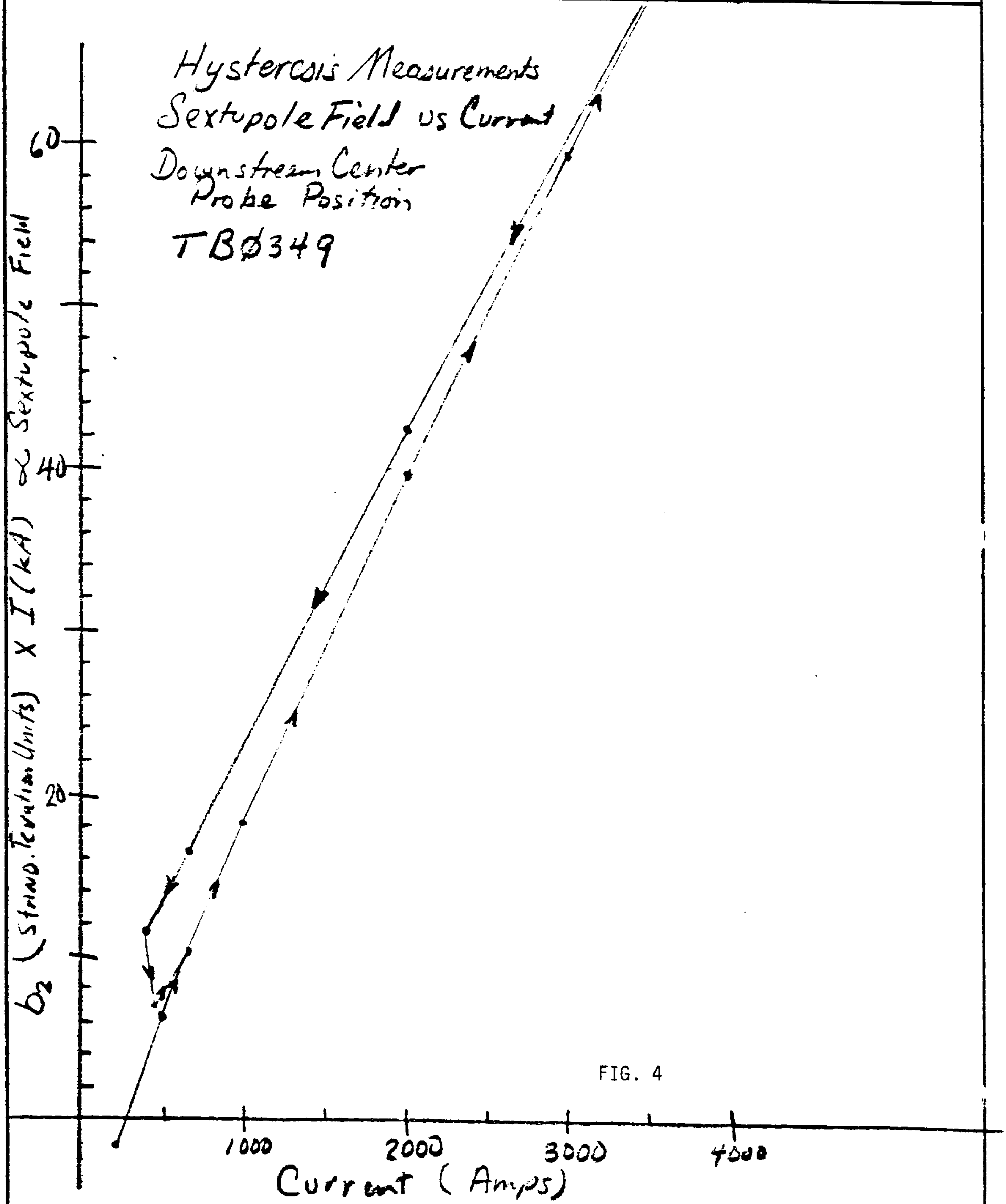
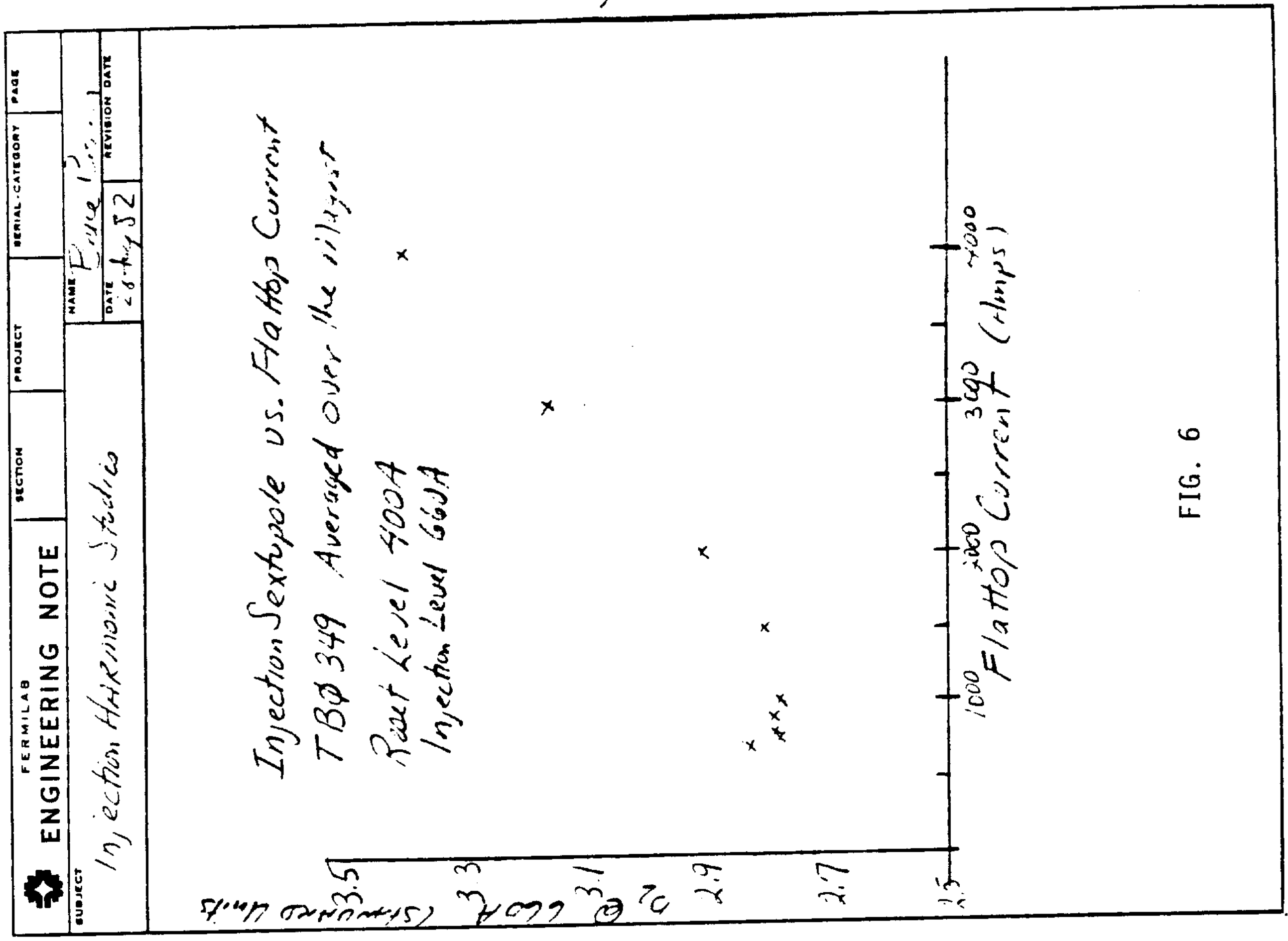


FIG. 4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PROJECT
SERIAL-CATEGORY
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NAME
DATE
26-Aug 82
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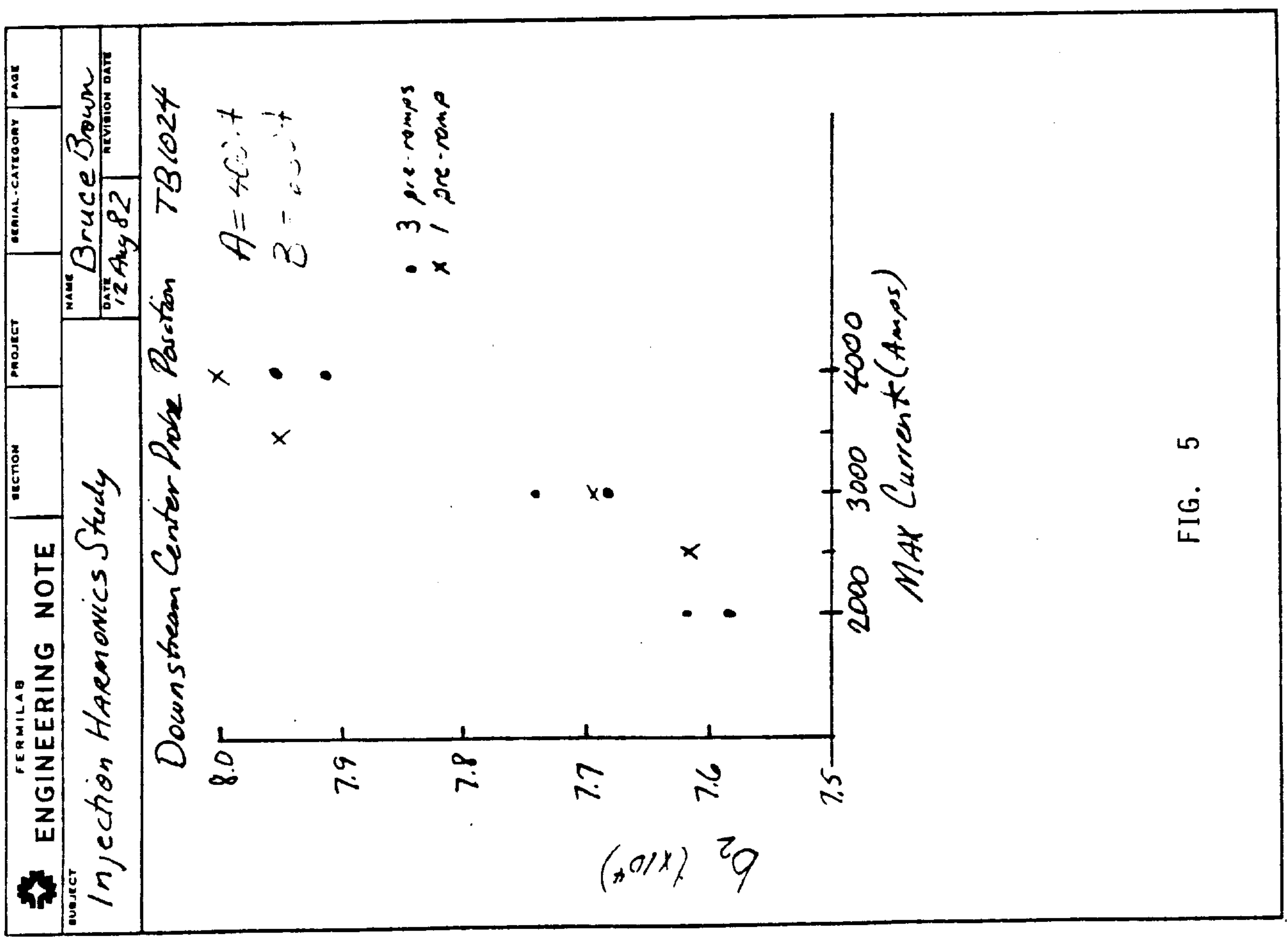
Injection Sextupole vs. FlatTop Current
TBØ349 Averaged over the magnet
Reset Level 400A
Injection Level 660A
2.5
2.7
2.9
3.1
3.3
3.5
b2 @ 660A (Standard Units)
1000
2000
3000
4000
FlatTop Current (Amps)

FIG. 6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SECTION
PROJECT
SERIAL-CATEGORY
PAGE
NAME
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Downstream Center Probe Position TB1024
• 3 pre-ramps
x 1 pre-ramp
7.5
7.6
7.7
7.8
7.9
8.0
b2 (x10^4)
2000
3000
4000
MAX Current (Amps)

FIG. 5

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SECTION -10-

PROJECT

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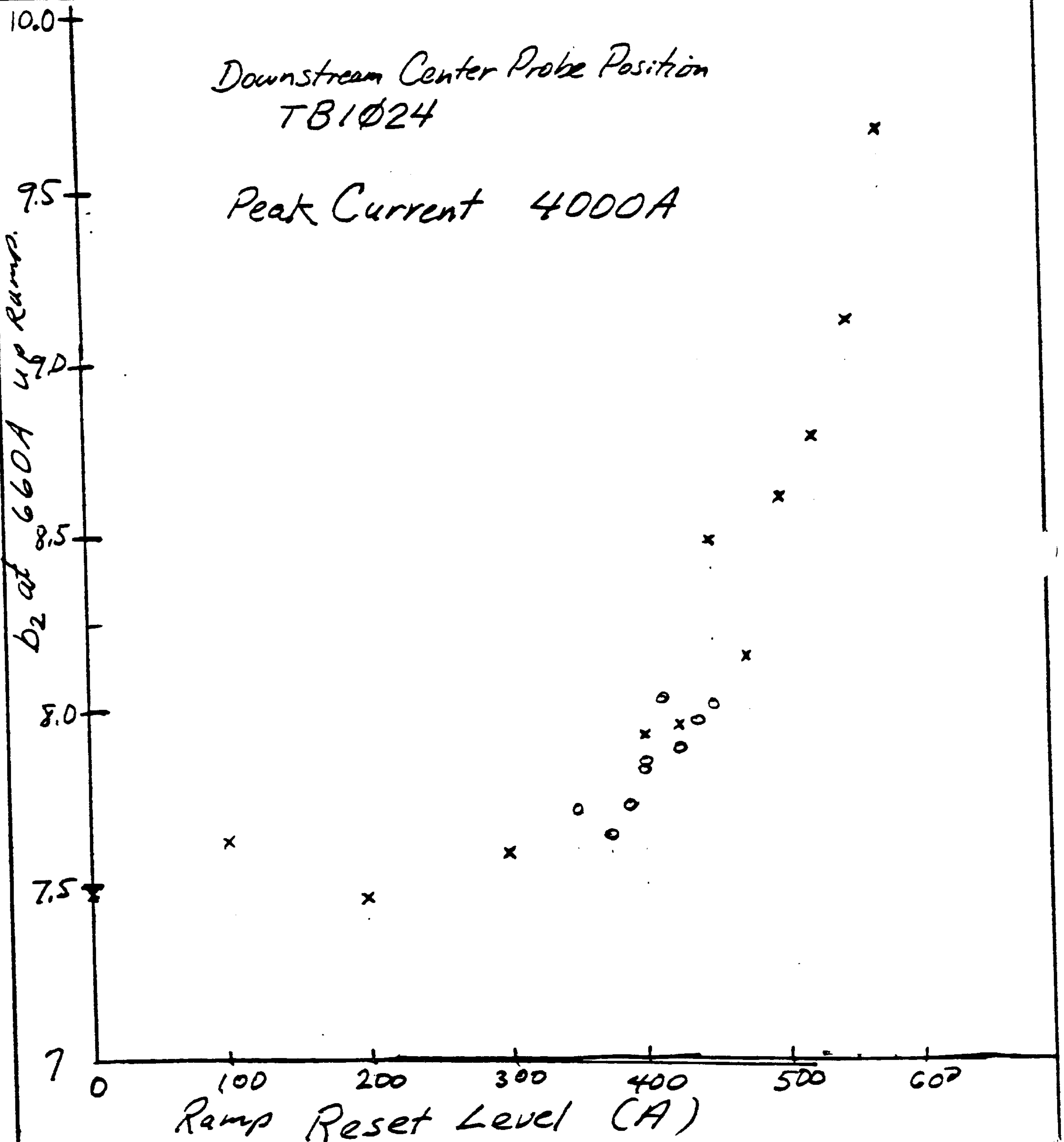
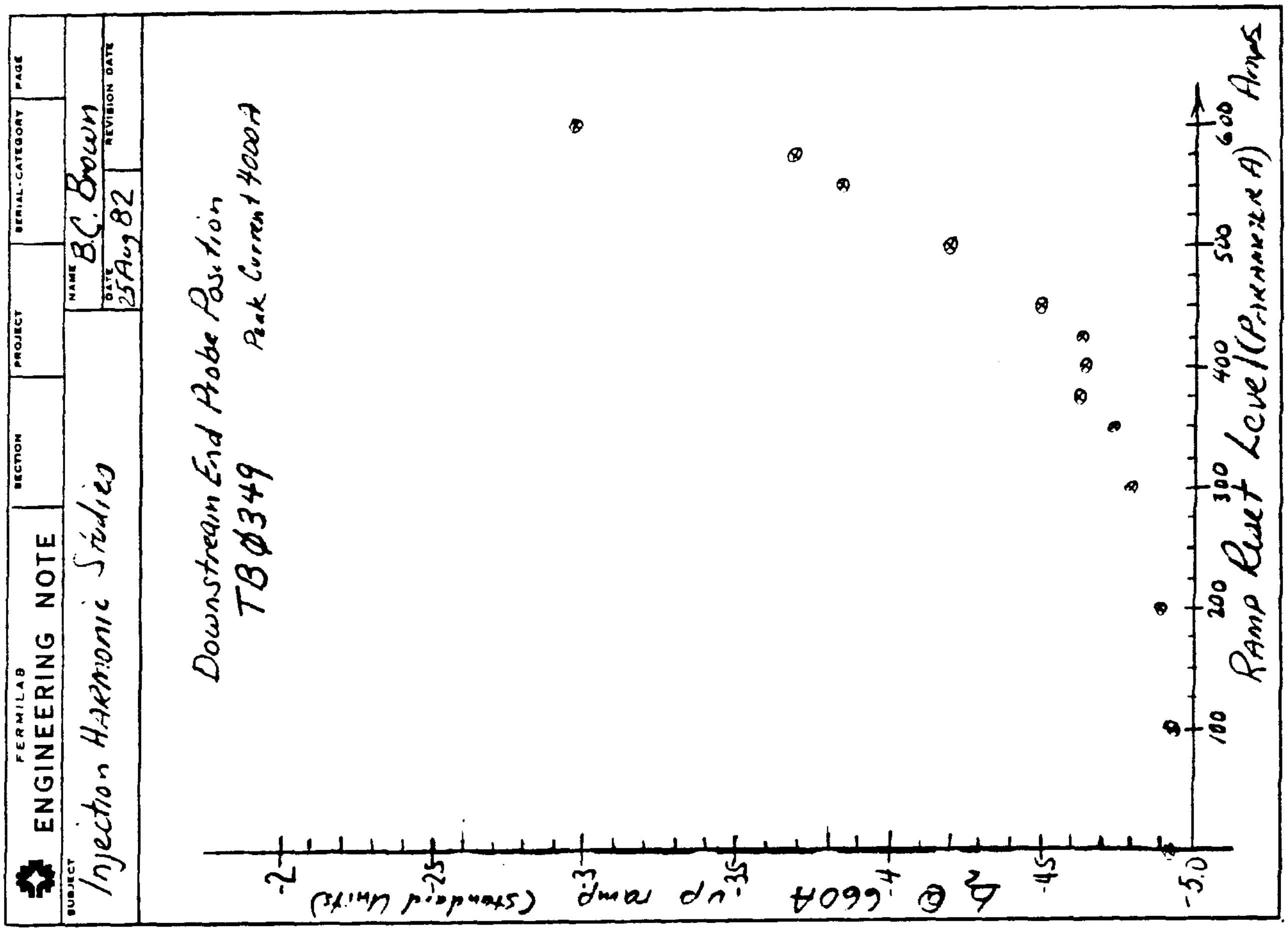


FIG. 7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SECTION
PROJECT
SERIAL-CATEGORY
PAGE
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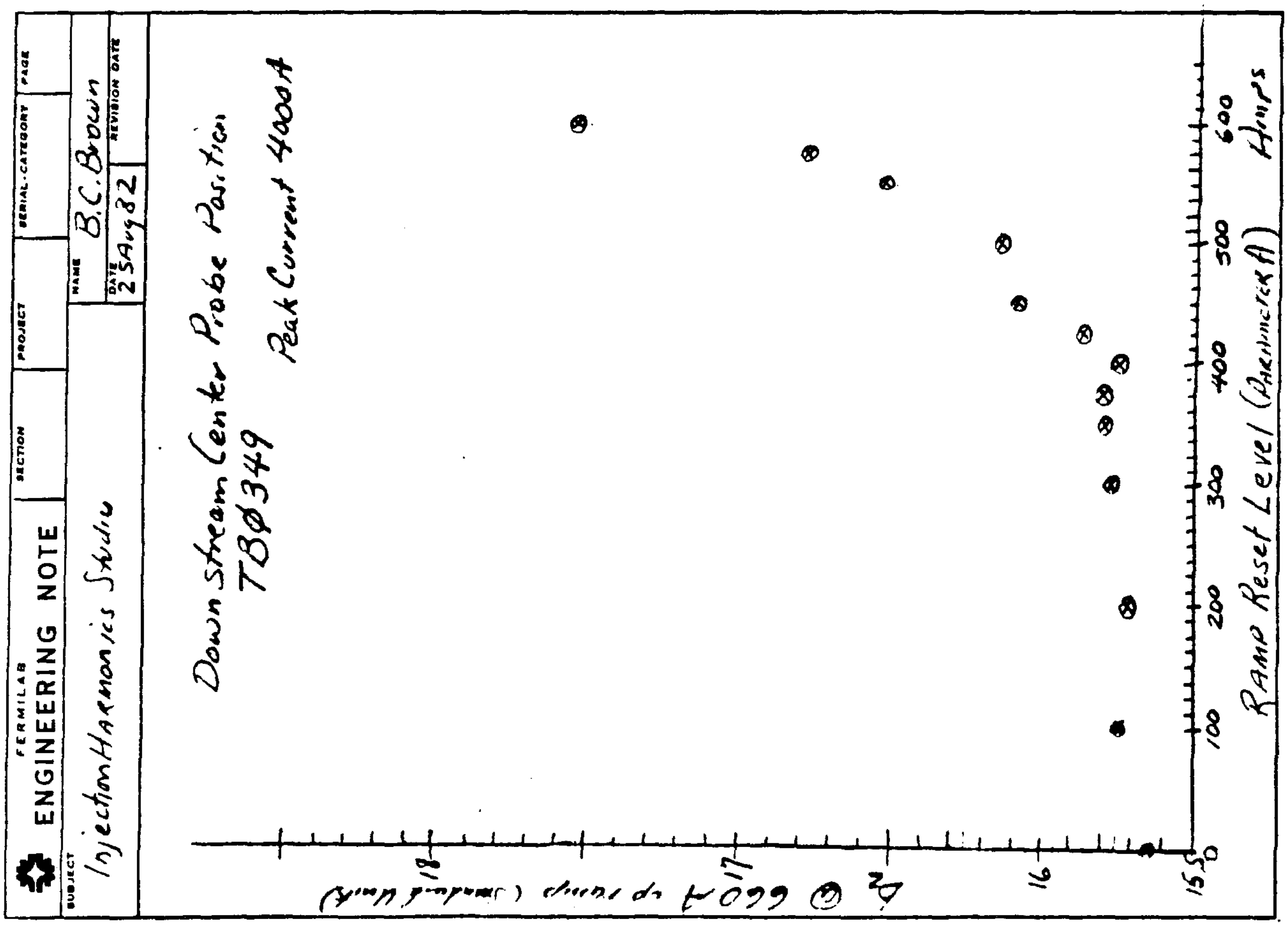
Downstream End Probe Position
TBØ349
Peak Current 4000A
Δ2 @ 660A up ramp (standard units)
-2
-2.5
-3
-3.5
-4
-4.5
-5.0
100
200
300
400
500
600
Ramp Reset Level (Parameter A) Amps

FIG. 8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SECTION
PROJECT
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PAGE
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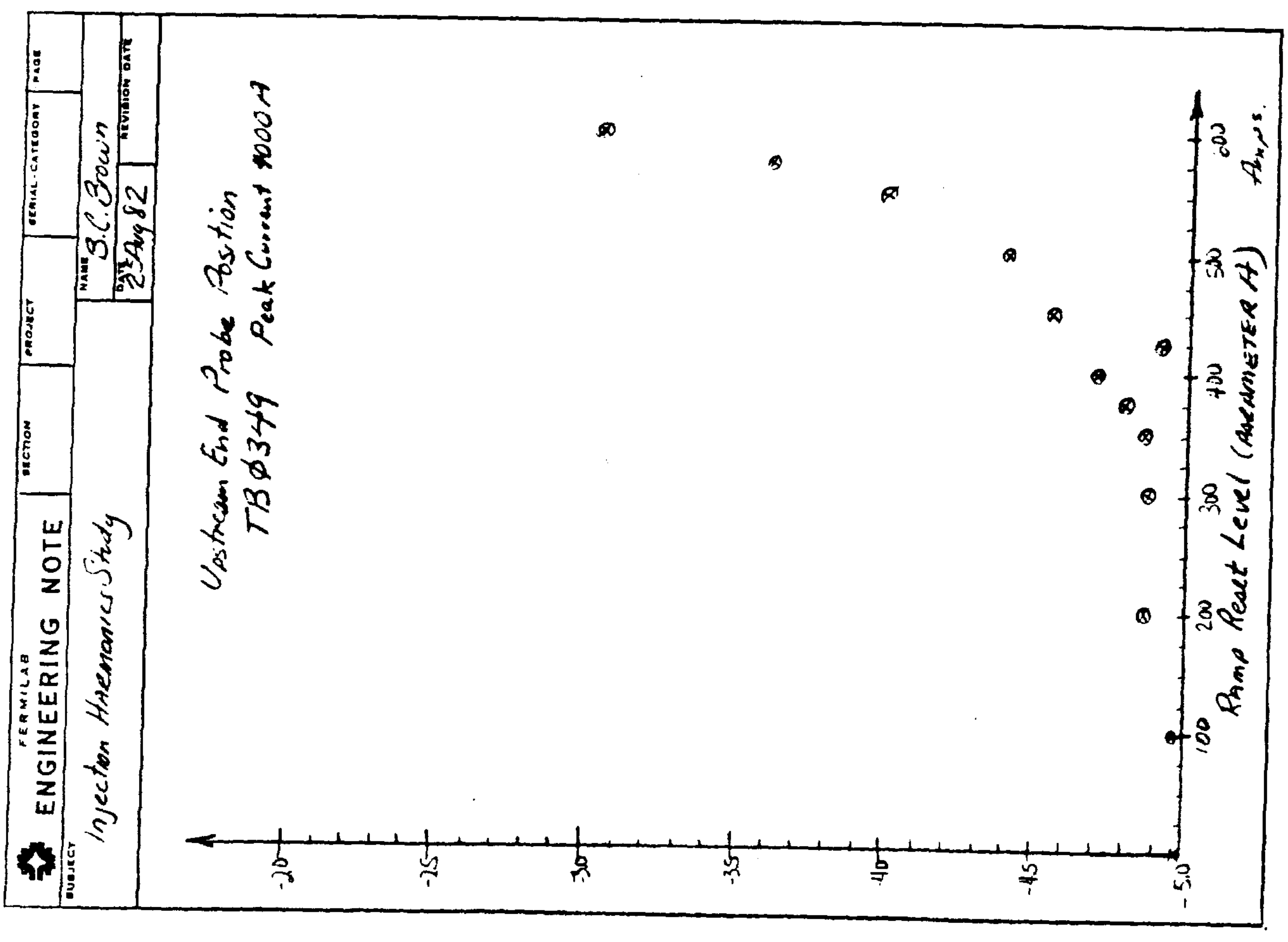
DATE 25Aug82
REVISION DATE
Down Stream Center Probe Position
TBØ349
Peak Current 4000A
Δ2 @ 660A up ramp (standard units)
18
17
16
15.5
0
100
200
300
400
500
600
Ramp Reset Level (Parameter A) Amps

FIG. 9



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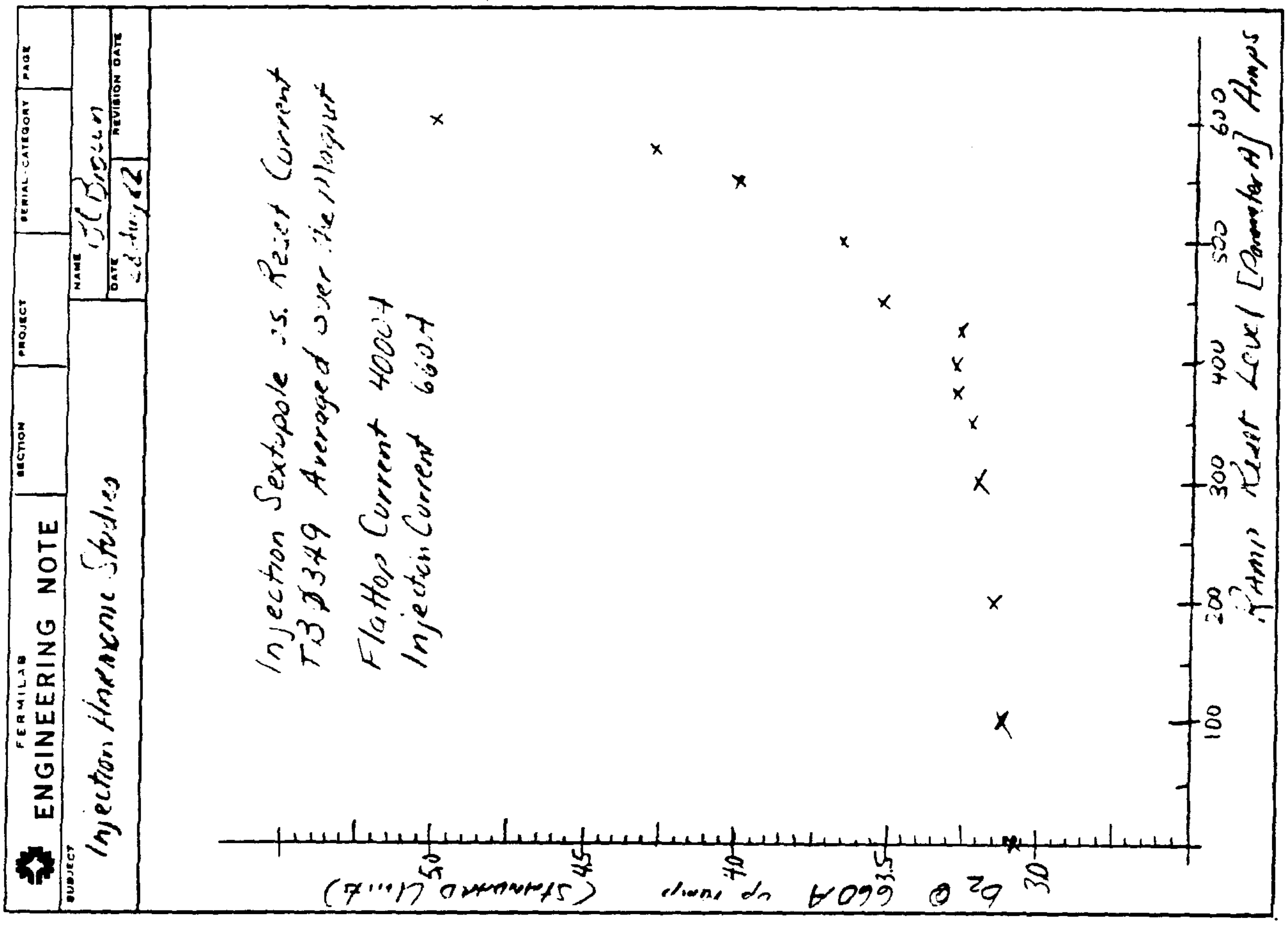
Upstream End Probe Position
TB0349 Peak Current 4000A
Ramp Reset Level (AMMETER A) Amps.

FIG. 10



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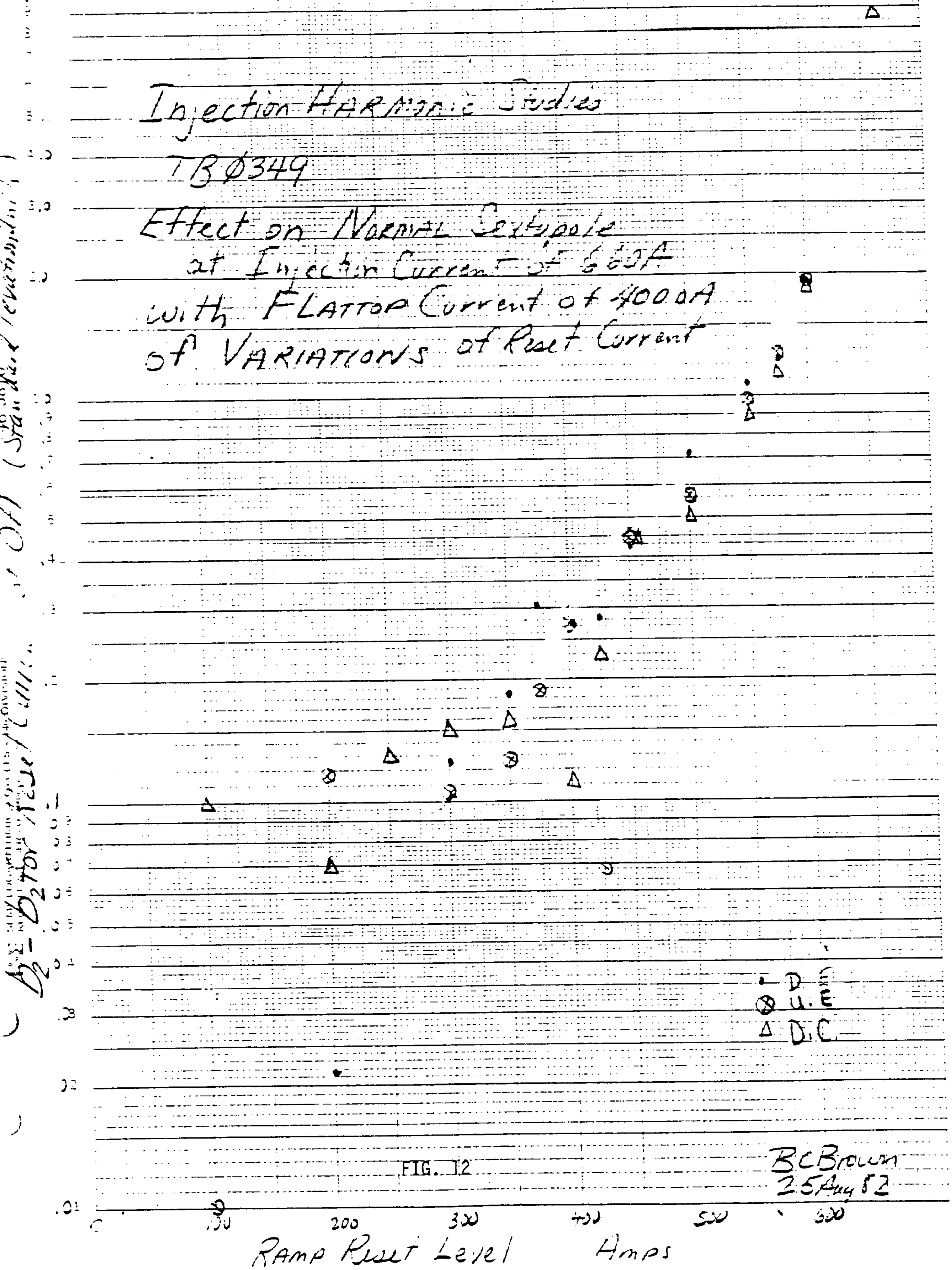
Injection Harmonic Studies
Injection Sextupole vs. Reset Current
TB0349 Averaged over the Magnet
FlatTop Current 4000A
Injection Current 660A
b2 @ 660A up ramp (Standard Units)
Ramp Reset Level [Ammeter A] Amps

FIG. 11


Injection Harmonic Studies
TB∅349
Effect on Normal Sextupole
at Injection Current of 660A
with Flattop Current of 4000A
of Variations of Reset Current
D.E
U.E
D.C.
0
100
200
300
400
500
600
Ramp Reset Level Amps
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25Aug82

FIG. 12

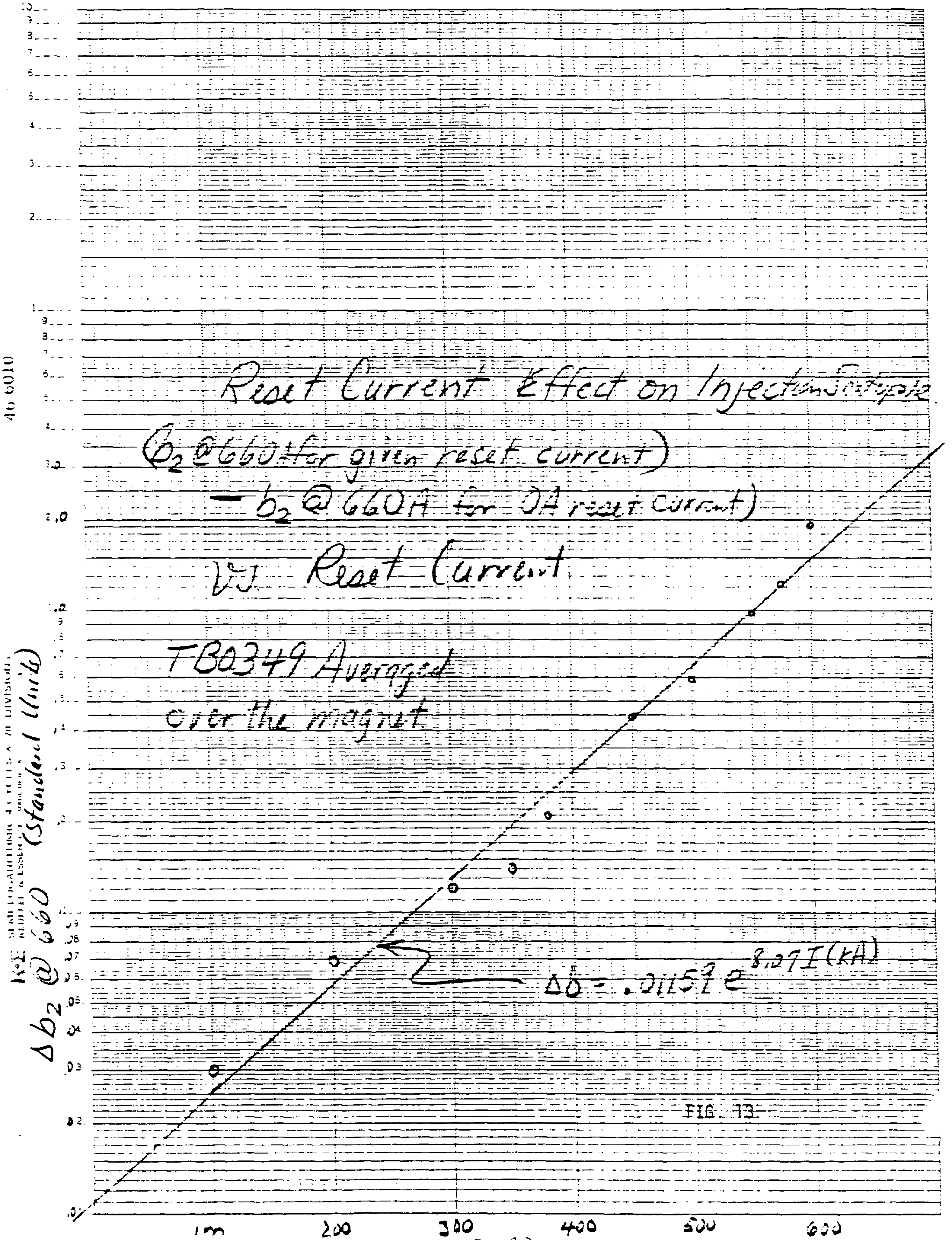
Reset Current Effect on Injection Sextupole
(b2 @660 for given reset current)
− b2 @660A for 0A reset current)
vs Reset Current
TB0349 Averaged
over the magnet
Δb2 @ 660 (Standard Unit)
Δb = .01151 e^8.07 I(kA)
200
300
400
500
600
46 6010

FIG. 13

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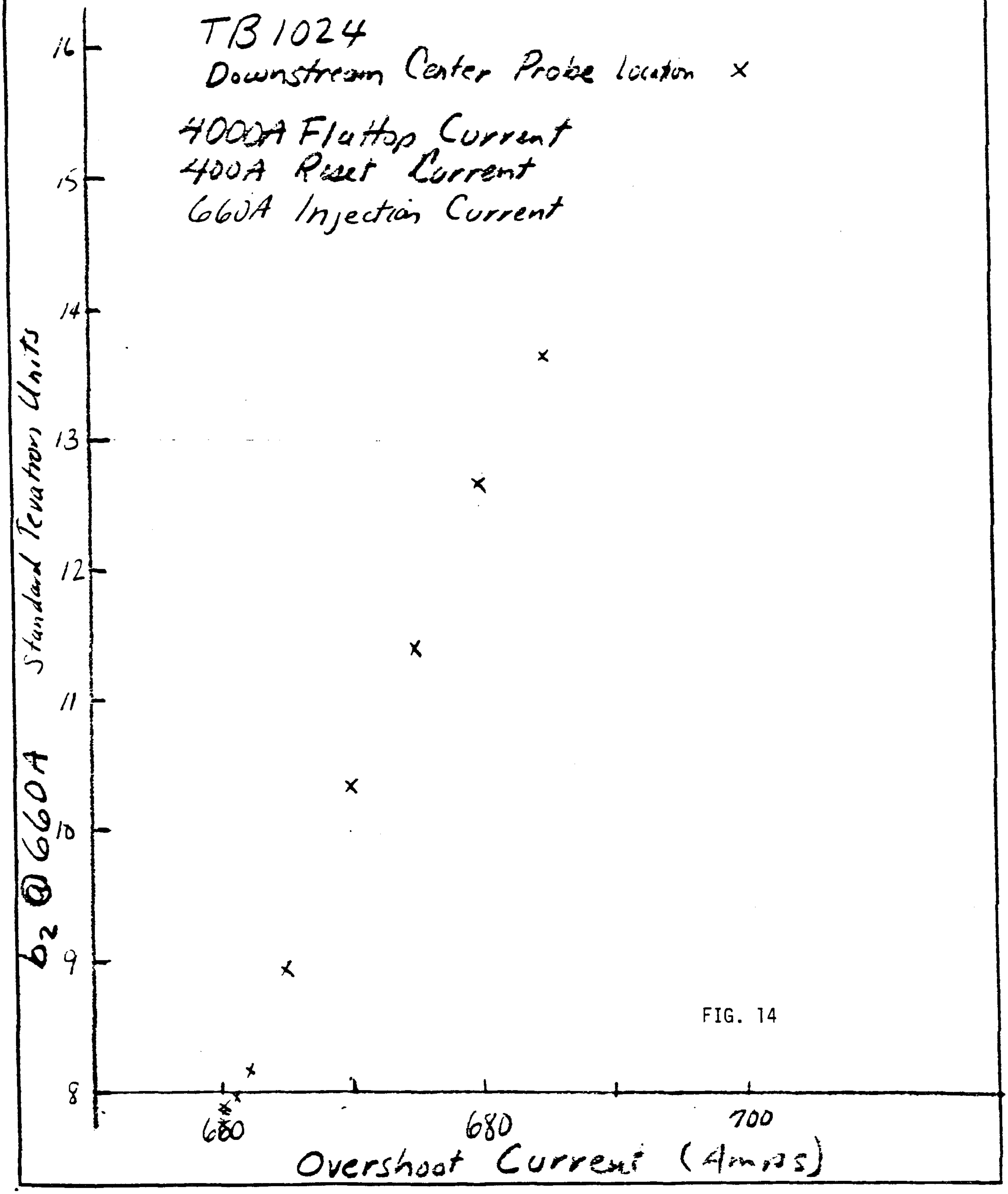

FIG. 14

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SECTION	PROJECT	SERIAL-CATEGORY	PAGE
-16-			

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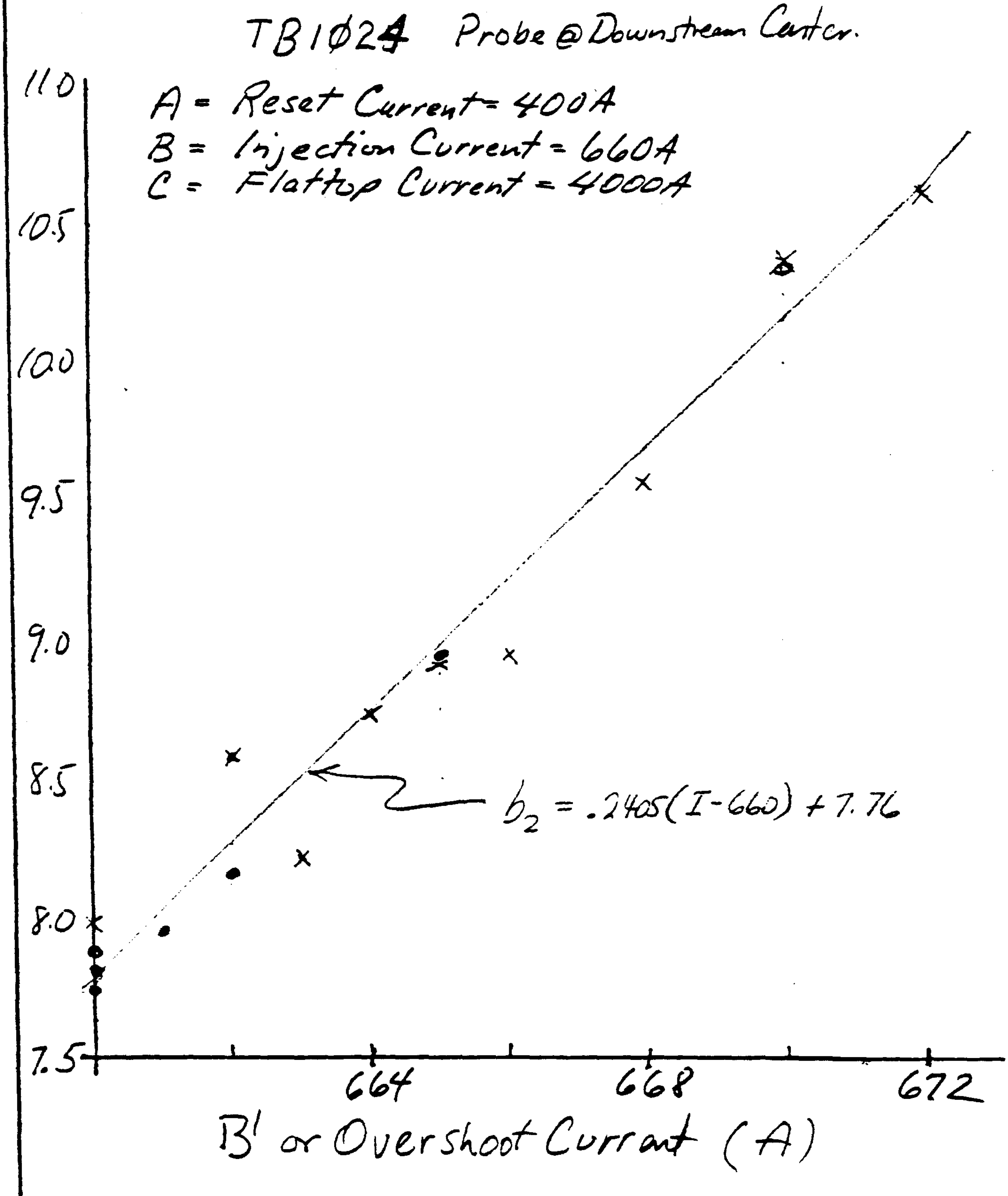

FIG. 15

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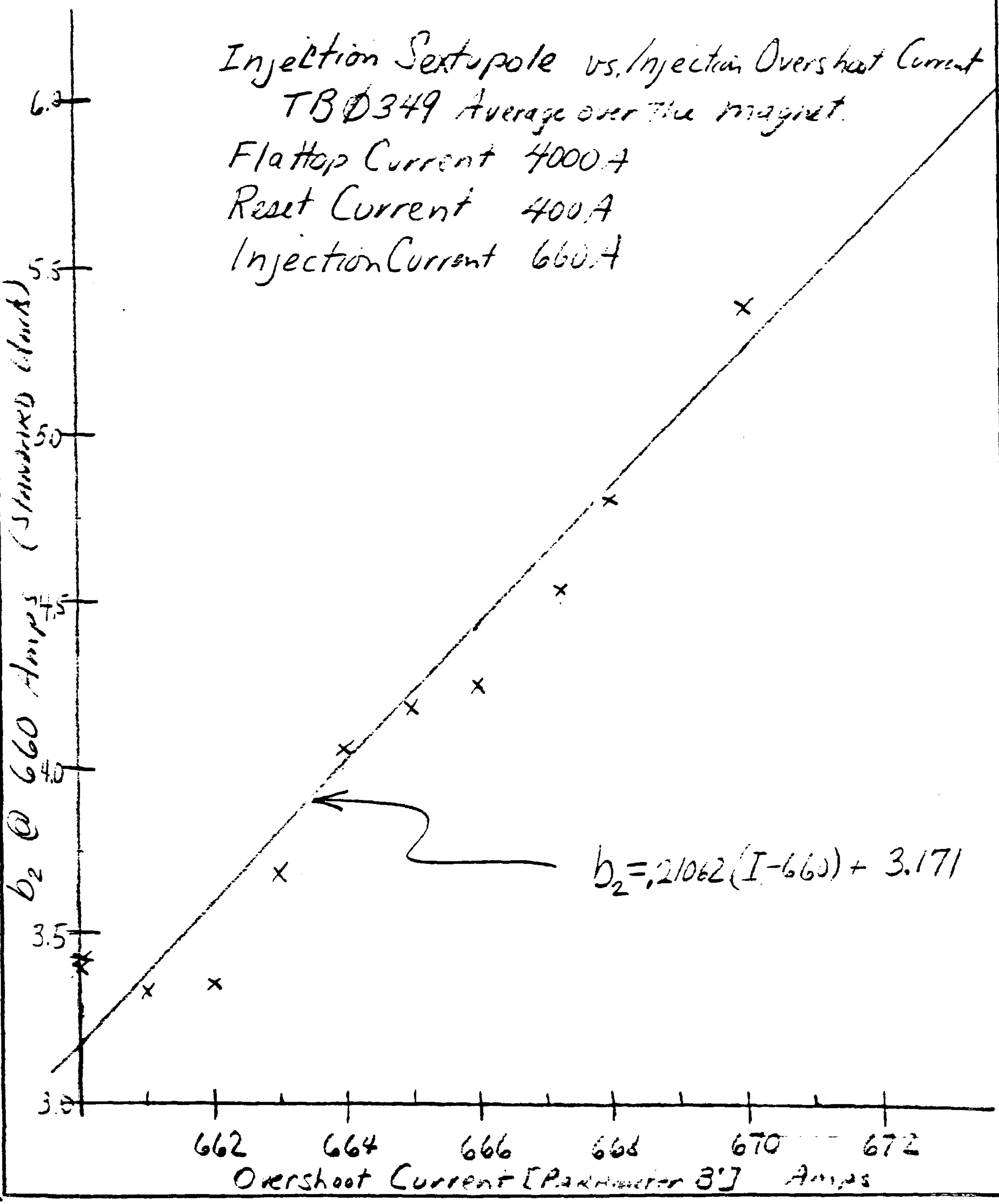

FIG. 16